

*Citation for published version:*

Burston, R, Mitchell, C & Astin, I 2016, 'Polar-cap plasma patch primary linear instability growth-rates compared', *Journal of Geophysical Research: Space Physics*, vol. 121, no. 4, pp. 3439-3451.  
<https://doi.org/10.1002/2015JA021895>

*DOI:*

[10.1002/2015JA021895](https://doi.org/10.1002/2015JA021895)

*Publication date:*

2016

*Document Version*

Early version, also known as pre-print

[Link to publication](#)

*Publisher Rights*

Unspecified

**University of Bath**

**Alternative formats**

If you require this document in an alternative format, please contact:  
[openaccess@bath.ac.uk](mailto:openaccess@bath.ac.uk)

**General rights**

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

**Take down policy**

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

**Title:**

**Polar-cap Plasma Patch Primary Linear Instability Growth-Rates Compared**

**Authors:**

Robert Burston, Department of Electronic and Electrical Engineering, The University of Bath,  
Claverton Down, Bath, UK.

Cathryn Mitchell, Department of Electronic and Electrical Engineering, The University of Bath,  
Claverton Down, Bath, UK.

Ivan Astin, Department of Electronic and Electrical Engineering, The University of Bath,  
Claverton Down, Bath, UK.

Corresponding author: I. Astin, Department of Electronic and Electrical Engineering, The  
University of Bath, Claverton Down, Bath, BA27AY, UK. ([eesia@bath.ac.uk](mailto:eesia@bath.ac.uk))

**Key Points.**

Growth rates for plasma linear instability processes are investigated

Turbulence, Gradient Drift and Current Convective Instabilities can all be important

## Abstract

Four primary plasma instability processes have been proposed in the literature to explain the generation of phase scintillation associated with polar-cap plasma patches. These are the Gradient Drift, Current Convective and Kelvin-Helmholtz instabilities and a small-scale “Turbulence” process. In this paper the range of possible values of the linear growth-rates for each of these processes is explored using Dynamics Explorer 2 satellite observations. It is found that the inertial Turbulence instability is the dominant process, followed by inertial Gradient Drift, collisional Turbulence and collisional shortwave Current Convective instabilities. The other processes, such as Kelvin-Helmholtz, collisional Gradient Drift and inertial shortwave Current Convective instabilities very rarely (<1% of the time) give rise to a growth rate exceeding 1/60, that is deemed to be significant (in publications) to give rise to GPS scintillation.

**Index terms:** 2439, 2471, 2772, 6929

## 1. Introduction

Large regions of enhanced electron concentration drifting according to an  $\mathbf{E} \times \mathbf{B}$  force from the auroral dayside ionosphere into the polar-cap region of the ionosphere were theorised by *Hill* [1963] as an explanation for “sporadic F” observations via  $f_oF2$  measurements in these areas. This theory was confirmed experimentally by *Buchau et al.* [1983] using optical all-sky camera images and the structures (100s – 1000s km in scale) became generally known as polar-cap

36 plasma patches. They were soon observed to cause radio scintillation on radio signals traversing  
37 them [e.g., *Weber et al.*, 1984]. Polar-cap plasma patches are also strongly correlated with  
38 backscatter of High Frequency (HF) Coherent Scatter Radar (CSR) signals, which occurs when  
39 the signals meet electron concentration irregularities [*Oksavik et al.*, 2006].

40 Irregularities cause scintillation through diffractive scattering [*Hargreaves*, 1992] or ionospheric  
41 lensing [*Booker and Majidihi*, 1981] of the signal. Scintillation inducing irregularities are  
42 considered to form through a cascade of energy from longer wavelengths to shorter ones in a  
43 manner analogous to that which occurs in the generation of turbulence in neutral fluids [*Kintner*  
44 *and Seyler*, 1985]. This requires some initial process to create wavelike structures in the plasma  
45 where there are none to start with – a primary plasma instability [*Kelley*, 2009].

46 A plasma instability is any wavelike structure that can grow exponentially in amplitude from  
47 some initial perturbation that is assumed to pre-exist. In order for this to happen, some source of  
48 free energy – energy available to do work – is required [*Mikhailovskii*, 1992]. Such energy  
49 derives from a combination of the Earth’s geo-magnetic field and electric field mapped from the  
50 magnetosphere to the high-latitude ionosphere, (day to night) electron density gradients and  
51 atmospheric gravity wave (TID) ‘seeding’ [e.g. *Hysell et al.*, 2014]. In this paper we consider  
52 only the linear regime, where the instability (consisting of alternating regions of higher and  
53 lower electron concentration) is assumed to grow exponentially in amplitude, at a particular  
54 growth rate. This linear regime is most likely to occur on the bottomside of the F-region, with  
55 non-linear processes dominating in the topside, particularly in the Equatorial region [*Hysell et*  
56 *al.*, 2014].

## 2. Theoretical background

In linear instability theory, the amplitude,  $A$ , of the unstable wave can be described as  $A = A_0 e^{\gamma t}$  where  $A_0$  is the amplitude of the initial perturbation,  $t$  is the elapsed time since the start of the instability process and  $\gamma$  is the linear growth-rate of the instability. If there is more than one possible mode in a given set of physical circumstances, the relative magnitudes of  $\gamma$  provide a measure of which process will dominate the formation of irregularities within the plasma patch. It should, therefore be possible to calculate  $\gamma$  for each process and determine which instability is ultimately responsible for radio scintillation associated with plasma patches [e.g., *Burston et al.*, 2009; 2010].

Doing this is complicated by the natural variation in the parameters that appear in the growth-rate equations from one patch to the next or even for a single patch, both spatially and temporally. For example, the electric field (which appears in all the growth-rate equations treated here) can be viewed as fluctuating in magnitude and direction around a quasi-D.C. component that in itself varies in magnitude and direction on a time scale of 10s of minutes and spatial scale of hundreds of kilometers [*Hanson et al.*, 1993] and the orientation of the field with respect to a gradient in electron concentration is always important. Hence, for any given instability the growth-rate can take a range of values, depending on the range of values possible for the parameters involved. For this reason different instabilities may dominate in different circumstances that depend on the frequencies of occurrence and ranges of values of various solar-terrestrial parameters that appear in growth-rate equations.

Several primary instabilities have been proposed as the cause of scintillation inducing irregularities associated with plasma patches. These are the Gradient Drift Instability (GDI),

which has received the most attention by researchers [e.g., *Burston et al.*, 2009; 2010; *Gondarenko, and Guzdar*, 1999; 2001; 2004a; 2004b; 2006a; 2006b; *Gondarenko et al.*, 2003; *Guzdar et al.*, 1998; *Sojka et al.*, 1998], the Current Convective Instability (CCI) which is a modification of the GDI [*Kelley*, 2009], a “turbulent” process [*Burston et al.*, 2010; *Earle and Kelley*, 1993; *Kelley*, 2009] and the Kelvin-Helmholtz Instability (KHI) [*Basu et al.*, 1990; *Carlson et al.*, 2007; *Gondarenko, and Guzdar*, 2006a; *Oksavik et al.*, 2012].

With four instabilities under examination it would be expected that there would be four growth-rate equations but for a single instability, there can in fact be more than one equation. This is because the growth-rates may differ in the collisional and inertial plasma regimes and in the long and short perturbation wavelength assumptions. In the inertial regime only the bulk electric fields are important. In the collisional regime, the effects of individual particles’ electric fields must be taken into account. The peak of the F-region (at ~300km) of the ionosphere represents a transitional region from collisional to inertial regimes (delineated by where the collisional growth rate and ion-neutral collision rate become equal). Thus, it is necessary to consider both situations [e.g. *Sojka et al.*, 1998]. Each instability is outlined below in its own section, with the appropriate growth-rate equations given.

## **2.1 The Gradient Drift Instability**

The Gradient Drift Instability (GDI) requires a horizontal gradient in electron concentration, parallel to the electric field and a vertical magnetic field. Polar-cap patches potentially meet all these requirements as the geo-magnetic field is approximately vertical in the polar-cap, the electric field has a large horizontal component and the patch itself has gradients in all horizontal directions [e.g., *Basu et al.*, 1990; *Burston et al.*, 2009; *Chaturvedi et al.*, 1994; *Gondarenko,*

102 *and Guzdar, 1999; 2001; 2004a; 2004b; 2006a; 2006b; Gondarenko and Guzdar, 2004a;*  
 103 *Gondarenko et al., 2003; Gondarenko and Guzdar, 1999; 2001; 2004b; 2006; Guzdar et al.,*  
 104 *1998]. The growth-rate in the collisional regime is given by*

$$105 \quad \gamma_{cGDI} = \frac{\mathbf{E} \times \mathbf{B}}{B^2} \left( \frac{\nabla n}{n} \right) \quad (1)$$

106 where  $\mathbf{E}$  is the electric field vector,  $\mathbf{B}$  is the magnetic field vector and  $n$  is the electron  
 107 concentration (Figure 1) and  $\nabla n$  is the gradient of electron concentration per metre (Figure 2). In  
 108 the inertial regime the growth rate is given by

$$109 \quad \gamma_{iGDI} = \left[ v_{in} \frac{\mathbf{E} \times \mathbf{B}}{B^2} \left( \frac{\nabla n}{n} \right) \right]^{\frac{1}{2}} \quad (2)$$

110 [*Sojka et al., 1998*] where  $v_{in}$  is the ion-neutral collision frequency, given by

$$111 \quad v_{in} = \pi n_n r^2 \left( \frac{4kT}{\pi M} \right)^{\frac{1}{2}} \quad (3)$$

112 where, in turn,  $r$  is the colliding particles' radius, assumed the same for all species and  $M$  is the  
 113 colliding species' mass, also assumed the same for all species.  $T$  is the temperature, assumed the  
 114 same for all species and  $n_n$  is the neutral concentration. The constant,  $k$ , is Boltzmann's constant  
 115 [*Kauzman, 1966*]. This formula for the ion-neutral collision frequency is in fact that for the  
 116 collision of two neutral species and a more accurate version would take into account the small  
 117 correction required for a singly ionized species colliding with a neutral species. The assumption  
 118 that  $T$  is the same for all species is valid in quiet geomagnetic conditions only ( $K_p < 2$ ) otherwise  
 119 the collision rate will be larger than those used in this study. In the following,  $n_n$  is taken as the

density of monatomic oxygen (figure 3) and  $T$  is the  $O^+$  ion temperature (figure 4) as these are the main constituents of the neutral and ionized atmosphere at F-region heights.

## 2.2 The Current Convective Instability

The Current Convective Instability may occur when the criteria for the GDI are met and current flows parallel to the magnetic field (z-axis). Additionally, the initial perturbation must have a finite component along the direction of  $\nabla n$  (y-axis). For the CCI, there is a wavelength dependency as well as a difference between the collisional and inertial regimes, leading to four equations [Chaturvedi and Ossakow, 1979; 1981; Huba, 1984; Kelley, 2009; Ossakow and Chaturvedi, 1979]:

The growth rate for the CCI, collisional long wavelength regime is given [e.g. Huba, 1984] by

$$\gamma_{lwcCCI} = -k_z \left( \frac{qB}{m_i v_{in}} \right) \left( \frac{n_1 - n_2}{n_1 + n_2} \right) \left( \frac{\mathbf{E} \times \mathbf{B}}{B^2} \right) \left\{ 1 + \left( \frac{k_z}{k_y} \right)^2 \left( \frac{q^2 B^2}{m_i m_e v_{in} v_{ei}} \right) \right\}^{-\frac{1}{2}} \quad (4)$$

where  $q$  is the charge on the electron,  $k_z$  and  $k_y$  are the wavenumbers in the z and y directions respectively,  $n_1$  and  $n_2$  are the electron concentrations either side of a step-boundary perturbation (with  $n_2 > n_1$ ),  $m_e$  is the mass of an electron,  $m_i$  is the mass of an ion and  $v_{ei}$  is the electron-ion collision frequency. The latter, in S.I. units, is given [e.g. Ichimaru, 1973] by

$$v_{ei} = \frac{nq^4}{4\pi\epsilon_0^2 m_e^{1/2} (3kT)^{3/2}} \ln \left[ 12\pi n \left( \frac{nq^2}{\epsilon_0 kT} \right)^{-3/2} \right] \quad (5)$$



138 The growth rate for the CCI collisional short wavelength regime is given [e.g. *Huba*, 1984] by

$$139 \quad \gamma_{swcCCI} = -\frac{k_z}{k_y} \left( \frac{qB}{m_i v_{in}} \right) \left( \frac{\nabla n}{n} \right) \left( \frac{\mathbf{E} \times \mathbf{B}}{B^2} \right) \left\{ 1 + \left( \frac{k_z}{k_y} \right)^2 \left( \frac{q^2 B^2}{m_i m_e v_{in} v_{ei}} \right) \right\}^{-1} \quad (6)$$

140 The growth rate for CCI inertial long wavelength regime is given [e.g. *Huba*, 1984] by

$$141 \quad \gamma_{lwiCCI} = \left( \frac{v_{ei} m_e B^2}{m_i \mathbf{E} \times \mathbf{B}} \right)^{1/3} \left[ k_y \left( \frac{n_1 - n_2}{n_1 + n_2} \right) \right]^{2/3} \frac{\mathbf{E} \times \mathbf{B}}{B^2} \quad (7)$$

142 CCI, inertial short wavelength:

$$143 \quad \gamma_{swiCCI} = \left( \frac{v_{ei} m_e n B^2}{4 m_i \mathbf{E} \times \mathbf{B} \nabla n} \right)^{1/3} \frac{\mathbf{E} \times \mathbf{B} \nabla n}{B^2 n} \quad (8)$$

144 The short wavelength regime applies when  $kL \ll 1$  and the long wavelength regime applies  
 145 when  $kL \gg 1$ , where  $k$  is the perturbation wavenumber and  $L = n/\nabla n$  is the electron  
 146 concentration gradient scale length.  $L$  is given by *Huba and Ossakow* [1980] as 10-100km. The  
 147 perturbation wavelength on a plasma patch will be of the order of several tens of km or less,  
 148 making the short wavelength equations the more applicable.

## 149 **2.3 Turbulence**

150 The Turbulence process was first put forward by *Kelley and Kintner* [1978] and further  
 151 examined in *Burston et al.* [2010] and *Kelley* [2009]. It takes into account the fact that the  
 152 electric field fluctuates around the quasi-D.C. component indicated by  $\mathbf{E}$  in the preceding  
 153 equations. If it is assumed that these fluctuations are random in direction then there is always a  
 154 direction in which the instability can occur. The growth-rate equation replaces the velocity

155 (given by  $(\mathbf{E} \times \mathbf{B})/B^2$ ) with its equivalent integrated over all relevant wavenumbers of the  
 156 fluctuations of the electric field.

$$157 \quad \left[ \int_{k_L}^{\infty} E(k)^2 dk \right]^{\frac{1}{2}} / B \quad (9)$$

158 where  $k_L$  is the smallest relevant wavenumber, in this case  $2\pi/(\text{scale of patch})$ , or of order  
 159  $2\pi/100,000\text{m}$ . Substituting Eq.9 into Eq.1 gives the growth rate for the turbulent collisional  
 160 regime as

$$161 \quad \gamma_{cT} = \left[ \int_{k_L}^{\infty} E(k)^2 dk \right]^{\frac{1}{2}} \left( \frac{\nabla n}{nB} \right). \quad (10)$$

162 Substituting Eq.9 into Eq.2 gives the growth for the turbulent inertial regime as

$$163 \quad \gamma_{iT} = \left\{ v_{in} \left[ \int_{k_L}^{\infty} E(k)^2 dk \right]^{\frac{1}{2}} \left( \frac{\nabla n}{nB} \right) \right\}^{\frac{1}{2}} \quad (11)$$

## 164 **2.4 Kelvin-Helmholtz Instability**

165 The idea that primary ordinary Kelvin-Helmholtz Waves structure plasma patches was examined  
 166 observationally by *Basu et al.* [1990] and modelled by *Gondarenko, and Guzdar* [2006a] who  
 167 concluded that primary shear slows the development of the GDI. The idea was advanced again  
 168 by *Carlson et al.* [2007] who, in contradiction of this earlier work suggested it would accelerate  
 169 the generation of irregularities. The Carlson hypothesis was further tested in a case-study by  
 170 *Oksavik et al.* [2012] where it was found not to be dominant over the GDI except in a narrow  
 171 band of wavelengths. The growth-rate used in these KHI studies of  $2\Delta U/L$  (where  $\Delta U$  is the  
 172 velocity change across a shear zone and  $L$  is the distance scale length) disguises the electric and

geomagnetic field dependence and is therefore not appropriate for comparison with the equations already given in this paper. Instead, the equation used here is derived as a special case of the dispersion relation equation given in *Mikhailovskii* [1992] for ordinary Kelvin-Helmholtz Waves.

$$\frac{(\omega - kV_1)^2}{C_{A1}^2} + \frac{(\omega - kV_2)^2}{C_{A2}^2} - 2k^2 = 0 \quad (12)$$

where  $C_1$  is the Alfven speed in zone 1,  $C_2$  is the Alfven speed in zone 2,  $V_1$  is the plasma velocity in zone 1 and  $V_2$  is the plasma velocity in zone 2 and  $k$  the perturbation wavenumber. If  $n_1$  and  $n_2$  are the electron densities in zone 1 and 2 respectively, then the Alfven speed is given by  $C_j^2 = \frac{B^2}{\mu_0(m_i + m_e)n_j}$  with  $j = 1$  or  $j = 2$  for the two different zones and  $m_i$  and  $m_e$  are the ion and electron masses respectively.

Assuming that the patch (taken as zone 1) is moving and its surroundings (taken as zone 2) is stationary then  $V_1 = V = |(\mathbf{E} \times \mathbf{B})/B^2|$  and  $V_2 = 0$ . Hence, Eq.12 becomes

$$\frac{(\omega - kV)^2}{C_1^2} + \frac{\omega^2}{C_2^2} - 2k^2 = 0 \quad (13)$$

Solving for  $\omega$  gives:

$$\omega = \left( \frac{kVC_2^2}{C_1^2 + C_2^2} \right) \pm \frac{\{4k^2V^2C_2^4 - 4(C_1^2 + C_2^2)(k^2V^2C_2^2 - 2k^2C_1^2C_2^2)\}^{\frac{1}{2}}}{2(C_1^2 + C_2^2)} \quad (14)$$

and a growth-rate (rightmost term) given by

$$\gamma_{KH} = \frac{k\{V^2 C_2^4 - (C_1^2 + C_2^2)(V^2 C_2^2 - 2C_1^2 C_2^2)\}^{\frac{1}{2}}}{(C_1^2 + C_2^2)} \quad (15)$$

which simplifies to

$$\gamma_{KH} = \frac{k C_1 C_2 \{2(C_1^2 + C_2^2) - V^2\}^{\frac{1}{2}}}{(C_1^2 + C_2^2)} \quad (16)$$

with instability condition

$$V^2 > 2(C_1^2 + C_2^2) \quad (17)$$

For unstable growth, there must be an imaginary component to  $\omega$ , which implies a negative square root in Eq.16.

Substituting  $V$ ,  $C_1^2$  and  $C_2^2$  into Eq.16 gives

$$\gamma_{KH} = \frac{k(n_1 n_2)^{1/2}}{(n_1 + n_2)} \left[ \frac{2B^2}{\mu_0(m_i + m_e)} \left( \frac{1}{n_1} + \frac{1}{n_2} \right) - \left( \left| \frac{\mathbf{E} \times \mathbf{B}}{B^2} \right| \right)^2 \right]^{1/2} \quad (18)$$

The instability condition becomes

$$\left| \frac{\mathbf{E} \times \mathbf{B}}{B^2} \right|^2 > \frac{2B^2}{\mu_0(m_i + m_e)} \left( \frac{1}{n_1} + \frac{1}{n_2} \right) \quad (19)$$

It is notable that the instability condition is independent of wavenumber but larger wavenumbers (shorter wavelengths) will grow faster.

The above four processes can be divided into two categories; those that are dependent on a specific geometrical relationship between the electric field and the electron concentration gradient and those that are not. The GDI, whether collisional or inertial, falls into the former category, whereas the others fall into the latter. Specifically, the GDI requires that the electric field be parallel to the gradient, which in turn means it will only operate on the trailing edge of a patch. (On the leading edge, the electric field would be anti-parallel to the gradient.) At first glance it might be thought that this should apply to the Turbulence process, too, but in fact, because it is assumed that the A.C. fluctuations in the electric field have no directional bias, all slopes are unstable approximately half the time.

It should be noted here that another possibility has been suggested for the structuring of plasma patches; particle precipitation during formation. Anisotropic precipitation of energetic particles from above the ionosphere would lead to localized regions of increased ionization and hence gradients in electron concentration within the plasma patch. By modifying  $n$  and  $\nabla n$  in the patch and causing localized heating, this process would affect the subsequent growth-rate of all plasma instabilities discussed here. This process would only occur during the formation of the patch and would cease once the patch left the region of the cusp [Oksavik *et al.*, 2012; Walker *et al.*, 1999]. Since it is not itself an instability process it cannot be directly investigated by the method outlined below.

### **3.0 Method**

The possible magnitudes of the growth-rate for the four processes discussed above (for both inertial and collisional regimes) are assessed below using some 550 days of data from the Dynamics Explorer 2 (DE2) satellite covering August 1981 to February 1983. Thus, the DE2

data are concentrated at the peak of solar-cycle (#21) and therefore do not represent a whole solar cycle. Similarly, only data recorded by the satellite when at 300 – 400 km altitude and greater than  $65^\circ$  magnetic latitude (north and south) are used in order to constraint our study to the F2 peak and polar cap regions. For illustration we do not separate the two hemispheres. However, it should be noted that there will be differences between hemispheres because of measurement times and the offset of the geographic from the geomagnetic and dip poles [e.g. *Coley and Heelis*, 1998]. The DE2 data were chosen as all of the parameters in the growth rates equations used are either directly observed by, or can be calculated from, DE2 observations, with a minimum in the way of approximation or assumption, except with regard to the electric field because of a partial instrument failure (discussed below) and the wavenumbers of initial perturbations, the range of values of which are assumed. Full details of the instruments aboard the satellite can be found in [*Hoffman et al.*, 1981]. In the following, the relative magnitudes of growth-rates for all the relevant processes are compared. This done by randomly sampling the data for each parameter, which are then use to calculate all possible values of growth-rate for each growth-rate equation.

The values of  $v_{in}$  and  $v_{ei}$  used in the following were calculated from DE2 data by using Eq.3 and Eq.5 respectively. The values for  $T$  are taken as the ( $O^+$ ) ion temperatures (whose histogram of occurrence is displayed in Figure 4),  $n_n$  is the neutral monatomic oxygen concentration (histogram of occurrence displayed in Figure 3) and  $n = n_i$  (i.e. the ion and electron concentrations are assumed equal and histogram of occurrence is displayed in Figure 1). The full field strength  $B$  (histogram of occurrence displayed in Figure 5) is also approximated by the

248 vertical magnetic field component ( $B_z$ ). In the following only the magnitude of the growth rate is  
249 calculated (vector quantities are replaced by scalar ones in all cases) simplifying the equations  
250 slightly.

251

252 The Electric field data comes from the Vector Electric Field Instrument (VEFI) on board DE2.  
253 This consisted of three mutually perpendicular instruments measuring orthogonal electric field  
254 strength components, allowing recovery of the full electric field strength vector  $\mathbf{E}$  [Heppner *et*  
255 *al.*, 1978a; 1978b]. Unfortunately the z-axis instrument did not deploy and no z-axis data were  
256 recorded. Because the axes were relative to the spacecraft, it is not possible to determine the  
257 components of the field in the Earth centred co-ordinate system without the z-axis data. Hence a  
258 method of approximating values of  $E = |\mathbf{E}|$  had to be applied. Examination of the relevant data  
259 recorded in the x-y plane (spacecraft co-ordinates) showed that 50% of the time the values of  
260 each component  $E_x$  and  $E_y$  were the same order of magnitude and over 90% of the time  $E_x$  and  
261  $E_y$  differed by no more than one order of magnitude (See Table 1). In the case of the A.C. field  
262 (see also Table 1) the  $E_x$  and  $E_y$  components also differed from each other by no more than one  
263 order of magnitude over 90% of the time. Since the spacecraft co-ordinate system continuously  
264 varied in relation to the Earth centred co-ordinate system, it was assumed that  $E_z$  would also  
265 rarely differ from  $E_x$  and  $E_y$  by more than this. Hence the approximation

266  $E_z^2 \approx (E_x^2 + E_y^2)/2$  was adopted, leading to

267 
$$E \approx \sqrt{\frac{3}{2}(E_x^2 + E_y^2)}. \quad (20)$$

Given all of the above, the equation used for the collisional GDI growth rate, Eq.1, becomes

$$\gamma_{cGDI} = \frac{E}{B} \frac{|\nabla n|}{n} \quad (21)$$

$\nabla n$  was derived from DE2 Langmuir probe observations of electron concentration  $n$  (as displayed in Figure 1) in the following manner: First, only data recorded at 300 – 400 km altitude were admitted, in order to retain only F-region altitudes. Second, only data at  $> 65^\circ$  magnetic latitude were admitted (in either hemisphere), in order to retain only geographical regions where patches plausibly occur. The  $65^\circ$  magnetic latitude was chosen to capture patches during storms equatorward of the polar cap, as patches are more prevalent during such storm time conditions. Third, only gradients in the remaining data, indicative of a plasma patch, were admitted. Such gradients were defined as being at least 40% slopes over a distance of 140 ( $\pm 5\%$ ) km, following [Coley and Heelis, 1995]. We believe that using this distance should exclude the smaller non-patch structures within the auroral oval. Such gradients were calculated by dividing the electron concentration data into sequences covering 140 ( $\pm 5\%$ ) km, performing a linear regression on them and taking the resulting straight-line slope as  $|\nabla n|$ . Note that such sequences may overlap each other and that these slopes do not necessarily represent the steepest gradients possible on a given structure as they are only the slope in the direction of motion of the satellite. The histogram of  $|\nabla n|$  occurrence, as derived from DE2 is displayed in Figure 2.

The values of all other parameters used in this and all subsequent cases were those observed during the time periods when admissible gradients were present. Hence the subset of the DE2



288 data used plausibly represents conditions within patches. No attempt has been made to  
 289 independently verify the existence of patches at these times and places.

290 For the inertial GDI case, Eq.2 becomes

$$291 \quad \gamma_{iGDI} = \left( v_{in} \frac{E|\nabla n|}{Bn} \right)^{1/2} \quad (22)$$

292 For the collisional, short wavelength CCI, Eq.6 becomes

$$293 \quad \gamma_{swcCCI} = \frac{k_z}{k_y} \left( \frac{qE|\nabla n|}{nm_i v_{in}} \right) \left\{ 1 + \left( \frac{k_z}{k_y} \right)^2 \left( \frac{q^2 B^2}{m_i m_e v_{in} v_{ei}} \right) \right\}^{-1} \quad (23)$$

294 For the inertial, short wavelength CCI, Eq.8 becomes:

$$295 \quad \gamma_{swiCCI} = \left( \frac{v_{ei} m_e |\nabla n|^2 E^2}{4m_i n^2 B^2} \right)^{1/3} \quad (24)$$

296 For the KHI, Eq.18 becomes

$$297 \quad \gamma_{KH} = \frac{k(n_1 n_2)^{1/2}}{(n_1 + n_2)} \left[ \frac{2B^2}{\mu_0(m_i + m_e)} \left( \frac{1}{n_1} + \frac{1}{n_2} \right) - \left( \frac{E}{B} \right)^2 \right]^{1/2} \quad (25)$$

298 with  $n_1$  and  $n_2$  taken as the maximum and minimum figures in the electron concentration used to  
 299 calculate  $|\nabla n|$ .

300 In Eqs.21-25, inclusive, the parameter,  $E$ , refers to the quasi-D.C. measurements of the electric  
 301 field. For the two Turbulence equations, the A.C. component is required. This was measured by  
 302 DE2 in the range 4Hz-1024Hz across eight channels, so the integral over the measured region  
 303 becomes  $\sum_{k=2\pi/1024}^{2\pi/4} E(k)^2$  taking Eq.20 into account for each  $E(k)$  before summation.

Eq.10, for the collisional turbulent growth rate becomes

$$\gamma_{cT} = \left( \sum_{k=2\pi/1024}^{2\pi/4} E(k)^2 \right)^{1/2} \left( \frac{|\nabla n|}{nB} \right) \quad (26)$$

For the inertial turbulent regime, Eq.11 becomes

$$\gamma_{iT} = \left\{ v_{in} \left( \sum_{k=2\pi/1024}^{2\pi/4} E(k)^2 \right)^{1/2} \left( \frac{|\nabla n|}{nB} \right) \right\}^{1/2} \quad (27)$$

The ideal approach to exploring the range of values of the growth rates for each process is to calculate a value of  $\gamma$  for every possible combination of the necessary input measurements (e.g. the Magnetic and Electric field data as summarized in Figures 5-7). However, given the subset of DE2 data selected this would become unmanageably large. Hence, in order to handle the number of output values of  $\gamma$  in a sensible time it was necessary to take representative samples of the full data sets of each input parameter. The method of simple random sampling was adopted, using the following equation to determine the minimum sample size,  $S$ , required:

$$S = p/[1 + p/P] \quad (28)$$

Where  $p = Z^2/(4M^2)$ ,  $M$  is the desired margin of error expressed as a fractional percentage,  $P$  is the size of the population being sampled and  $Z$  is a factor chosen dependent on the required confidence limit. The practical memory constraint led to the best possible sampling regime of a

95% confidence limit, corresponding to  $Z = 1.95$ , and a margin of error of 9% ( $M = 0.09$ ) leading to a sample size of  $\sim 116$  for each parameter (as given in Table 2).

#### 4. Results

In general there are two sources of error relating to these results: instrument error and sampling error. The former applies to all the basic input measurements and introduces some level of uncertainty in their values; these are then combined when the calculation is made, generating an over-all level of uncertainty that could be estimated from the individual uncertainties. The second arises since, instead of calculating gamma for every possible combination of input measurements (a practical impossibility) a representative sample of each input population has been used, instead. Again, an overall uncertainty due to this sampling could be calculated and combined with the instrumental error. However there is a third source of error relating specifically to the electric and magnetic fields. These have been taken as their full-field magnitudes when, more rigorously, the horizontal and vertical components, respectively, should be used. This introduces an over-estimating bias in both of these measurements. Finally, the approximation necessitated by the failure of the z-axis Langmuir probe to deploy leads to an error in the electric field magnitude such that the values used can only be considered accurate to order-of-magnitude. This final source of error swamps the others. Hence, all values of  $\gamma$  presented below should be considered to be only order-of-magnitude accurate.

In [Carlson *et al.*, 2007] evidence for a rise-time ( $1/\gamma$ ) of 60s or less is presented for patches still in the cusp region. Hence, in the following the various growth rate mechanisms are compared to find which can give values for  $\gamma > 1/60$  and under what circumstances. The percentage of derived growth rates (using the sample data) exceeding,  $1/6$ ,  $1/60$  and  $1/600$  for each of the four processes are presented in Table 3. All processes except Kelvin-Helmholtz Instabilities (KHI) are found capable of giving rise-times less than 60s using the DE2 data. For collisional Gradient Drift and shortwave inertial Current Convective instabilities this occurs less than 1% of the time, but occurs for the majority of the time for inertial Turbulence instabilities and around 10% of the time for inertial Gradient Drift and collisional Turbulence and shortwave Current Convective instabilities.

## 5. Conclusions

The derived distributions of possible linear growth-rates for each mechanism show that only Turbulence, inertial GDI and shortwave collisional CCI would regularly give the rise-times of approximately 60s or less observed in the cusp region during patch formation [e.g. Carlson *et al.*, 2007 and references there-in]. However, the relative importance of the various mechanisms could be significantly different in the non-linear regime [Gondarenko, and Guzdar, 2006; Gondarenko and Guzdar, 2004a; Gondarenko *et al.*, 2003; Gondarenko and Guzdar, 1999; 2004b; Guzdar *et al.*, 1998]. In this regard, the linear regime assumes the instability grows exponentially in amplitude, at the growth rate  $\gamma$  given by the above. Whilst there are various mechanisms that can drive an instability, one possibility is an increasing velocity shear,  $\delta V$  (due to an exponentially increasing perturbation in electric field,  $\delta E = \delta E_0 e^{\gamma t}$ ) which over time could

become large enough to drive secondary, Kelvin-Helmholtz Instabilities (KHI) that damp the growth of the instability, ending the linear growth regime. Based on Eq. 19, taking  $n_1 = n + \delta n$ ,  $n_2 = n - \delta n$  (where  $n$  is the background electron density) and making the not unreasonable assumptions that  $n^2 \gg \delta n^2$  and  $m_i + m_e \approx m_i$ , this occurs for the ordinary KHI when  $t > t_c$  where

$$t_c \sim \left(\frac{1}{\gamma}\right) \ln \left( \frac{2B^2}{\delta E_0} \sqrt{\frac{1}{\mu_0 n m_i}} \right) \quad (28)$$

Using the sample mean values for  $B$ ,  $E$  and  $n$  this would indicate that the linear regime would likely last for a duration of order  $10/\gamma$ . This would indicate that grow rates greater than  $1/6$  would imply that the mechanism becomes non-linear within minutes, whereas growth rates less than  $1/600$  would take several hours for the mechanism to become unstable.

There are two limitations with regard to the method deployed here for comparing growth-rates for candidate irregularity generating mechanisms associated with polar-cap plasma patches that cannot easily be overcome. First, the data are concentrated at the peak of solar-cycle 21 (late 1981 – early 1983) and therefore do not represent a whole solar cycle. Second, there is a tacit assumption that all the input variables in the growth-rate equations are uncorrelated with all of the others. This may not be entirely accurate, especially with regard to the electric and magnetic fields and the electron concentration and its gradient.

Because the output values of growth rate are considered accurate only to order of magnitude, the relatively limited sampling of the populations is not considered a significant draw-back. Nor is the use of full field values of the electric and magnetic fields or the approximation made in order to obtain values of electric field strength in the absence of z-axis data.

It is remarkable that under the conditions selected as representative of patches, the A.C. component of the electric field is often larger than the quasi-D.C. component. This implies that the Turbulence process can be a cause of scintillation on its own and that all slopes of a patch can, in the right circumstances, be sufficiently unstable to cause measurable phase scintillation. In the past it has been assumed that patches showing irregularities or scintillation through-out all regions, rather than just on the trailing edge had undergone the GDI to such an extent that the irregularities had penetrated throughout the patch having started forming only on the trailing edge. The present results show that the same situation could be obtained by the action of the Turbulence process on all slopes, with irregularities forming on the entire circumference and working towards the centre. In this situation the maximum irregularity amplitude need only be the radius of the patch, rather than the entire diameter. This mechanism would therefore appear at first glance to take approximately half the time to cause irregularities to form through-out an entire patch. In fact, because the electric field is fluctuating in magnitude and direction, the growth rate in any one particular direction should be halved. The time to reach complete instability is still accelerated, however.

The values of  $\gamma_{GDI}$  and  $\gamma_T$  obtained suggest that irregularities should be observed in association with most patches. This is not backed by the observational record on either count. The explanation arises from the use here of local, linear theory to obtain the growth-rate equations used. Non-local, 3-dimensional, non-linear theory tends to strongly reduce growth-rate values and introduces wavelength dependencies if none were present in the local, linear theory [e.g., *Gondarenko et al.*, 2003; *Gondarenko and Guzdar*, 1999; 2001; 2004a; 2004b; 2006a; 2006b; *Guzdar et al.*, 1998; *Kelley*, 2009]. It is possible, that results may differ if non-linear processes dominate.

This does not affect the main conclusion that the KHI is not important as it was negligible to start with. However, these results are based on the statistical analysis, and thus in this context the KHI is not the main player for the patch structuring. However, these results do not exclude the situation where the KHI dominates under conditions of the strong flow shears. Nor is the conclusion that Turbulence is a process that must be taken into account affected, as its rise-time will be reduced to a similar extent to that for the GDI, but not more so. If, taking the full complexities into account, none of the processes considered here can give a rise-time less than 60s, then the most probable explanation of the appearance of phase scintillation very rapidly, whilst the patch is still in the cusp, is that inhomogeneous precipitation of energetic particles into the patch as it is forming accelerates the action of the GDI and/or Turbulence processes [*Oksavik et al.*, 2012].

425 To completely understand what is happening, an extension of the work in *Gondarenko et al.*  
 426 [2003]; *Gondarenko and Guzdar* [1999; 2001; 2004a; 2004b; 2006a; 2006b] and *Guzdar et al.*  
 427 [1998] must be made so that the effects of particle precipitation during formation are included,  
 428 along with the effects of the A.C. electric field. Additionally, the patch geometry and initial  
 429 electron concentration distribution should take account of recent observations in order to be fully  
 430 realistic. (The assumption that patches are approximately circular through-out their life-time,  
 431 having been demonstrated by Ionospheric Ray Tomography to be particularly unsound [e.g., *Yin*  
 432 *et al.*, 2009].)

433

434 Further complications arise when compound processes are considered. For example GDI and  
 435 Turbulence processes will be acting on the trailing edge of the patch at the same time. For such  
 436 processes, the ratio  $\gamma_{GDI}/\gamma_T$  indicates which dominates. This is given by

$$437 \quad \frac{\gamma_{GDI}}{\gamma_T} = \frac{|E_{D.C.}|}{\left[ \int_{k_L}^{\infty} (E_{A.C.}(k))^2 \right]^{1/2}} \quad (29)$$

438 Hence, this can be obtained whenever simultaneous measurements of both the D.C. and A.C.  
 439 components are available. Unless one or the other (or both) is negligible, the compound action of  
 440 both will accelerate irregularity production compared to either one acting alone. This could lead  
 441 to a situation where radar back-scatter from irregularities is present throughout a patch but  
 442 stronger from the trailing edge. The relative impact of Turbulence vs. the GDI should also be  
 443 more thoroughly examined by analysis of observational data based on Eq.29 for each admissible  
 444 electron concentration gradient. In this regard, it is interesting that comparing the quasi-D.C. and  
 445 A.C. electric field strengths (Figures 6 and 7) shows that, under the conditions described for the



selection of the data above, the summed A.C. field is usually stronger than the quasi-D.C. field  
and Turbulence dominates (Figure 8).

## Acknowledgements

This work is supported by the United Kingdom's Engineering and Physical Sciences Research  
Council grant EP/H003304/1 ("GNSS scintillation: detection, forecasting and mitigation"). The  
data used in this paper comes from the Dynamics Explorer (DE2) satellite via NASA's National  
Space Science Data Centre (available at [ftp://nssdcftp.gsfc.nasa.gov/spacecraft\\_data/de/de2/](ftp://nssdcftp.gsfc.nasa.gov/spacecraft_data/de/de2/)).

## References

- Basu, S., S. Basu, E. Mackenzie, W. R. Coley, J. R. Sharber, and W. R. Hoegy (1990), Plasma structuring by the gradient drift instability at high-latitudes and comparison with velocity shear driven processes, *Journal of Geophysical Research-Space Physics*, 95(A6), doi:10.1029/JA095iA06p07799.
- Booker, H. G., and G. Majidihi (1981), Theory of refractive scattering in scintillation phenomena, *Journal of Atmospheric and Terrestrial Physics*, 43(11), 1199-1214, doi:10.1016/0021-9169(81)90035-0.
- Buchau, J., B. W. Reinisch, E. J. Weber, and J. G. Moore (1983), Structure and dynamics of the winter polar cap region, *Radio science*, 18(6), 995-1010.
- Burston, R., I. Astin, C. Mitchell, L. Alfonsi, T. Pedersen, and S. Skone (2009), Correlation between scintillation indices and gradient drift wave amplitudes in the northern polar ionosphere, *Journal of Geophysical Research-Space Physics*, 114, doi:10.1029/2009ja014151.
- Burston, R., I. Astin, C. Mitchell, L. Alfonsi, T. Pedersen, and S. Skone (2010), Turbulent times in the northern polar ionosphere?, *Journal of Geophysical Research-Space Physics*, 115, doi:10.1029/2009ja014813.
- Carlson, H. C., T. Pedersen, S. Basu, M. Keskinen, and J. Moen (2007), Case for a new process, not mechanism, for cusp irregularity production, *Journal of Geophysical Research: Space Physics*, 112(A11), A11304, doi:10.1029/2007JA012384.

476 Chaturvedi, P. K., M. J. Keskinen, S. L. Ossakow, and J. A. Fedder (1994), Effects of Field Line  
 477 Mapping on the Gradient-Drift Instability in the Coupled E-Region and F-Region High-Latitude  
 478 Ionosphere, *Radio Science*, 29(1), 317-335.

479 Chaturvedi, P. K., and S. L. Ossakow (1979), Non-Linear Stabilization of the Current  
 480 Convective Instability in the Diffuse Aurora, *Geophysical Research Letters*, 6(12), 957-959.

481 Chaturvedi, P. K., and S. L. Ossakow (1981), The Current Convective Instability as Applied to  
 482 the Auroral Ionosphere, *Journal of Geophysical Research-Space Physics*, 86(NA6), 4811-4814.

483 Coley, W. R., and R. A. Heelis (1995), Adaptive Identification and Characterization of Polar  
 484 Ionization Patches, *Journal of Geophysical Research-Space Physics*, 100(A12), 23819-23827.

485 Coley, W. R., and R. A. Heelis (1998), Seasonal and universal time distribution of patches in the  
 486 northern and southern polar caps, *Journal of Geophysical Research-Space Physics*, 103(A12),  
 487 29229–29237, doi:10.1029/1998JA900005.

488 Gondarenko, N. A., and Guzdar (2004a), Plasma patch structuring by the nonlinear evolution of  
 489 the gradient drift instability in the high-latitude ionosphere, *Journal of Geophysical Research-*  
 490 *Space Physics*, 109(A9).

491 Gondarenko, N. A., Guzdar, J. J. Sojka, and M. David (2003), Structuring of high latitude  
 492 plasma patches with variable drive, *Geophysical Research Letters*, 30(4).

493 Gondarenko, N. A., and P. N. Guzdar (1999), Gradient drift instability in high latitude plasma  
 494 patches: ion inertial effects, *Geophysical Research Letters*, 26(22), 3345-3348.

495 Gondarenko, N. A., and P. N. Guzdar (2001), Three-dimensional structuring characteristics of  
 496 high-latitude plasma patches, *Journal of Geophysical Research-Space Physics*, 106(A11),  
 497 24611-24620, doi:10.1029/2000ja000440.

498 Gondarenko, N. A., and P. N. Guzdar (2004b), Density and electric field fluctuations associated  
 499 with the gradient drift instability in the high-latitude ionosphere, *Geophysical Research Letters*,  
 500 31(11).

501 Gondarenko, N. A., and Guzdar (2006a), Nonlinear three-dimensional simulations of mesoscale  
 502 structuring by multiple drives in high-latitude plasma patches, *Journal of Geophysical Research-*  
 503 *Space Physics*, 111(A8).

504 Gondarenko, N. A., and P. N. Guzdar (2006b), Simulations of the scintillation-producing  
 505 irregularities in high-latitude plasma patches, *Geophysical Research Letters*, 33(22),  
 506 doi:10.1029/2006gl028033.

507 Guzdar, P. N., N. A. Gondarenko, P. K. Chaturvedi, and S. Basu (1998), Three-dimensional  
 508 nonlinear simulations of the gradient drift instability in the high-latitude ionosphere, *Radio*  
 509 *Science*, 33(6), 1901-1913, doi:10.1029/98rs01703.

510 Hanson, W. B., W. R. Coley, R. A. Heelis, N. C. Maynard, and T. L. Aggson (1993), A  
 511 comparison of in-situ measurements from Dynamics Explorer-2, *Journal of Geophysical*  
 512 *Research-Space Physics*, 98(A12), 21501-21516, doi:10.1029/93ja01422.

513 Hargreaves, J. K. (1992), *The Solar-Terrestrial Environment*, Cambridge University Press.

514 Heppner, J. P., E. A. Bielecki, T. L. Aggson, and N. C. Maynard (1978a), Instrumentation for  
 515 DC and low-frequency electric-field measurements on ISEE-A, *Ieee Transactions on Geoscience*  
 516 *and Remote Sensing*, 16(3), 253-257, doi:10.1109/tge.1978.294557.

517 Heppner, J. P., N. C. Maynard, and T. L. Aggson (1978b), Early results from ISEE-1 Electric-  
 518 field measurements, *Space Science Reviews*, 22(6), 777-789.

519 Hill, G. E. (1963), Sudden enhancements of f-layer ionization in polar regions, *Journal of the*  
 520 *Atmospheric Sciences*, 20(6), 492-497, doi:10.1175/1520-0469(1963)020<0492:seolii>2.0.co;2.

521 Hoffman, R. A., G. D. Hogan, and R. C. Maehl (1981), Dynamics Explorer spacecraft and  
 522 ground operations systems, *Space science instrumentation*, 5(4), 349-367.

523 Huba, J. D. (1984), Long Wavelength Limit of the Current Convective Instability, *Journal of*  
 524 *Geophysical Research-Space Physics*, 89(NA5), 2931-2935.

525 Huba, J. D., and S. L. Ossakow (1980), Influence of magnetic shear on the current convective  
 526 instability in the diffuse aurora, *Journal of Geophysical Research-Space Physics*, 85(NA12),  
 527 6874-6876, doi:10.1029/JA085iA12p06874.

528 Hysell, D. L., R. Jafari, D. C. Fritts, and B. Laughman (2014), Gravity wave effects on  
 529 postsunset equatorial F region stability, *J. Geophys. Res. Space Physics*, 119, 5847–5860,  
 530 doi:10.1002/2014JA019990.

531 Ichimaru, S. (1973), *Basic Principles of Plasma Physics*, W. A. Benjamin, Inc.

532 Kauzman (1966), *Kinetic Theory of Gases*, W. A. Benjamin.

533 Kelley, M. (2009), *The Earth's Ionosphere: Plasma Physics and Electrodynamics*, 2nd ed., 556  
 534 pp., Elsevier.

535 Kelley, M. C., and P. M. Kintner (1978), Evidence for 2-Dimensional inertial turbulence in a  
 536 cosmic-scale low-beta plasma, *Astrophysical Journal*, 220(1), 339-&, doi:10.1086/155911.

537 Kintner, P. M., and C. E. Seyler (1985), The Status of Observations and Theory of High-Latitude  
 538 Ionospheric and Magnetospheric Plasma Turbulence, *Space Science Reviews*, 41(1-2), 91-129.

539 Mikhailovskii, A. B. (1992), *Electromagnetic Instabilities in an Inhomogeneous Plasma*,  
 540 Institute of Physics Publishing, Bristol.

541 Oksavik, K., J. Moen, M. Lester, T. A. Bekkeng, and J. K. Bekkeng (2012), In situ  
 542 measurements of plasma irregularity growth in the cusp ionosphere, *Journal of Geophysical*  
 543 *Research-Space Physics*, 117, doi:10.1029/2012ja017835.

544 Oksavik, K., J. M. Ruohoniemi, R. A. Greenwald, J. B. H. Baker, J. Moen, H. C. Carlson, T. K.  
 545 Yeoman, and M. Lester (2006), Observations of isolated polar cap patches by the European  
 546 Incoherent Scatter (EISCAT) Svalbard and Super Dual Auroral Radar Network (SuperDARN)  
 547 Finland radars, *Journal of Geophysical Research-Space Physics*, 111(A5),  
 548 doi:A0531010.1029/2005ja011400.

549 Ossakow, S. L., and P. K. Chaturvedi (1979), Current Convective Instability in the Diffuse  
 550 Aurora, *Geophysical Research Letters*, 6(4), 332-334.

551 Schunk and Nagy (2000), *Ionospheres: Physics, plasma physics and Chemistry*, Cambridge  
 552 University Press.

553 Sojka, J. J., M. V. Subramaniam, L. Zhu, and R. W. Schunk (1998), Gradient drift instability  
554 growth rates from global-scale modeling of the polar ionosphere, *Radio Science*, 33(6), 1915-  
555 1928.

556 Walker, I. K., J. Moen, L. Kersley, and D. A. Lorentzen (1999), On the possible role of  
557 cusp/cleft precipitation in the formation of polar-cap patches, *Annales Geophysicae-Atmospheres*  
558 *Hydrospheres and Space Sciences*, 17(10), 1298-1305, doi:10.1007/s00585-999-1298-4.

559 Weber, E. J., J. Buchau, J. G. Moore, J. R. Sharber, R. C. Livingston, J. D. Winningham, and B.  
560 W. Reinisch (1984), F-layer ionization patches in the polar-cap, *Journal of Geophysical*  
561 *Research-Space Physics*, 89(NA3), 1683-&, doi:10.1029/JA089iA03p01683.

562 Yin, P., et al. (2009), Imaging of the Antarctic ionosphere: Experimental results, *Journal of*  
563 *Atmospheric and Solar-Terrestrial Physics*, 71(17-18), 1757-1765,  
564 doi:10.1016/j.jastp.2009.09.014.

565

566

567 **Figure Captions**

568 Figure 1: Histogram of DE2 electron concentration data.

569 Figure 2: Histogram of the gradient of electron concentration as derived from DE2 data.

570 Figure 3: Histogram of the DE2 neutral monatomic oxygen concentration data.

571 Figure 4: Histogram of the DE2 O<sup>+</sup> ion temperature data.

572 Figure 5: Histogram of DE magnetic field strength data.

573 Figure 6: Histogram of the quasi-D.C. electric field strength data.

574 Figure 7: Histogram of the A.C. electric field data (as summed over the measured range of 4Hz-  
575 1024Hz).

576 Figure 8: The percentage of derived growth rates exceeding the given growth rate for  
577 ‘turbulence’ (Turb) and gradient drift (GDI) in both the inertial and collisional regimes. The  
578 inertial turbulent regime is most likely to exceed any given growth rate and is therefore the more  
579 important.

580

581